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SPATIAL VARIATIONS OF SHEET FLOW AND SEDIMENT TRANSPORT ON AN AGRICULTURAL FIELD

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ABSTRACT

This paper presents the spatial and temporal variations of sheet flow and sediment transport on an agricultural field under natural rainfall. The study site is located in western France (Rennes, Brittany) where rainfall amount and intensity are moderate. It is a field of garden-peas presenting a convex–concave gentle slope where only sheet flow is observed. A network of simple, low-cost collectors is used to measure sheet flow and sediment transport along the slope and to estimate the spatial variability for a given position on the slope. The water and sediment discharge was measured for each rainfall event from February to June. The analysis of space and time variations according to the characteristics of the rainfall events, changes in vegetation and soil crusting shows that the sheet flow is low and the runoff coefficient decreases as the slope length increases. Infiltration is particularly active in concave parts of the hillslope whatever the characteristics of the rainfall events. Sediment transport decreases in time as the soil crusts and vegetation develops.

KEY WORDS sheet flow; sediment transport; topography; sheet flow collectors; Armorican massif

INTRODUCTION

Sheet flow, i.e. a thin, continuous sheet of water running on the soil surface, induces a spatial redistribution of water and particles on the slope and, therefore, of absorbed or dissolved molecules of fertilizers and pesticides. This redistribution determines the acquisition of water chemistry on the hillslope, and possibly preferential locations for infiltration or deposition that may induce soil toxicity symptoms such as are sometimes observed downslope (Auzet, 1987, 1990). Complex processes act along the hillslope, consisting of a succession in space of infiltration and overland flow generation, of sediment removal and deposition whose relative magnitude varies in time according to the characteristics of the rainfall events. The variations in space are related to microtopography and the local soil physical properties. This may be indirectly related to the macrotopography: for example soil sealing depends on slope steepness (Poesen, 1992). Macrotopography also directly affects these variations in space: for example, runoff decreases and infiltration increases as the slope length increases (Poesen and Bryan, 1989; Molinier *et al.*, 1991; Poesen, 1992). This scale effect was shown on homogeneous plots (Dulay and Ackerman, 1934; Mutchler and Greer, 1980).

Time and space variations of numerous factors such as the characteristics of the rainfall events, the soil surface, the soil moisture and the slope morphology must be taken into account to explain the spatial structure of overland flow and sediment transport. Several authors have studied the problem of spatial variations of overland flow and sediment transport according to the slope (De Ploey, 1969; Poesen, 1981; Mathier and Roy, 1993) and this remains a critical point in hydrological and hydrochemical modelling.

This paper presents a method for analysing the spatial variations of overland flow and sediment transport in an agricultural field under gentle climate and topography in western France (Rennes, Brittany). The experimental design consists of a network of simple, unbounded and non-overlapping plots. The amount of water and sediment by plot was measured after each rainfall event. This network allows measurements

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Figure 1. The study field at the beginning of the study period when the devices were being set up

both of the spatial variations according to the slope length and of the spatial variability for the same position on the slope. Only a few papers take this approach (Bonell and Williams, 1987; Williams and Bonell, 1987; Mathier and Roy, 1993).

MATERIAL AND METHODS

The study field is located near Rennes (Brittany, France). The area has a temperate Atlantic climate. The mean annual rainfall is about 750 mm. The mean rainfall intensity is always lower than 40 mm h^{-1}; most of the time it is much lower, ranging from 0·1 to 5 mm h^{-1} on 168 days per year; rainstorms over 10 mm h^{-1} occur on only 17 days per year (Larivière and Verdou, 1976). The study field (Figure 1) presents a regular slope of about 4·5 per cent for 200 m, changing progressively to 1·5 per cent over the last 50 m, resulting in a slightly concave downslope element. The bedrock is composed of primary Brioverian shales. Soils are loamy, about 70 per cent loam, with low content of clay and organic matter, respectively about 17 and 2 per cent. The precise soil texture was determined between 10 and 20 cm in depth at three positions on the slope (Table 1) and shows that the finest textures are observed upslope and downslope. Soils are very sensitive to compaction with weak structural stability. Overland flow and sheet erosion result mainly from soil sealing and from compaction due to implement tracks (Bruneau and Gascuel-Odoux, 1990; Gascuel-Odoux *et al.*, 1991).

Cultivation consisted of garden peas that were sown in rows running directly downslope. The spacing between the rows was 18 cm. The microrelief combined two aspects. First, the wheel tracks induced slight

Table I. Soil texture, organic matter and pH measured at 10–20 cm in depth at three positions on the slope

	Clay	Silt		Sand			
	< 2 μm	2–20 μm	20–50 μm	50–200 μm	> 200 μm	pH	Organic matter (%)
Upslope	15·6	22·7	47·3	9·9	4·5	6·8	1·98
Midslope	14·7	26·1	47·9	7·2	4·1	6·4	1·81
Downslope	17·2	26·8	42·2	8	5·8	7·2	2·1

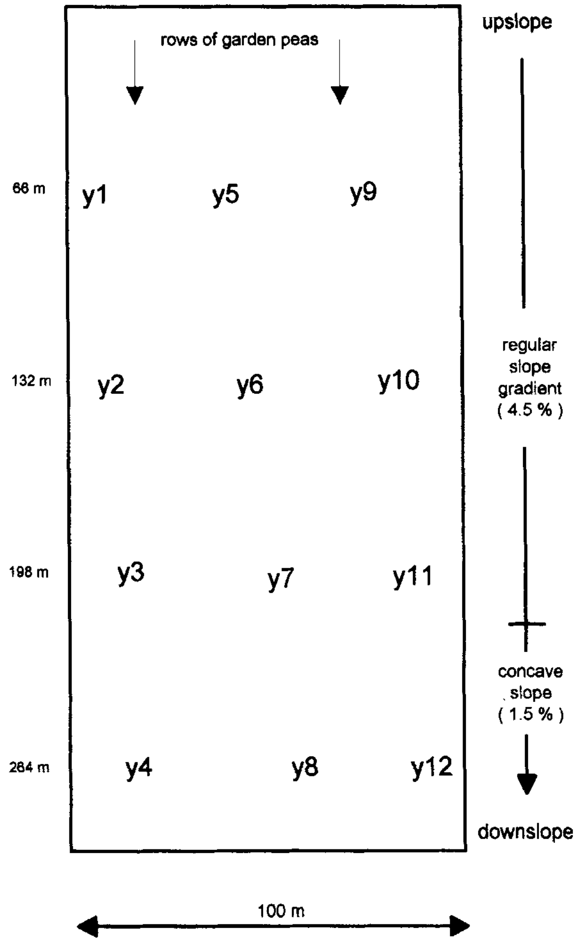

Figure 2. The network of unbounded and non-overlapping plots on the agricultural field

elevation differences of 2 to 3 cm every 4 m: these tracks were smoothed over during the sowing operations and were scarcely visible on the soil surface. Second, a clear elevation difference of 7 to 8 cm was caused by the cultivation rows but softened with time.

Twelve sampling points were chosen for collecting surface water and sediment: three sampling points were located at four regularly spaced positions on the slope (Figure 2). In detail, for each sampling point, the collector was set where the runoff was likely to be most important according to the soil surface aspect and in a row that would not be used by the tractor for subsequent herbicide spreadings. The distributors are usually very wide and the tractor does not take all the rows for spreading.

The collectors were designed to be cheap and easy to install and remove when required for crop harvesting and sowing. Each collector (Figure 3) comprises two PVC plates 0·7 m long forming an isosceles triangle. These plates are fixed vertically in the soil by a cement. This cement is covered by a quickly polymerized liquid resin to avoid disintegration of the cement by surface water. Unlike a former prototype design for tropical conditions (Planchon, 1991), the triangular collecting area is not protected by a resin because there is no risk of rilling in this context and because any resin would be taken off due to the high frequency of soil wetting and drying cycles. Moreover, this avoids any modification of the natural surface and allows the development of biological and fissural macropores. The two PVC plates are stuck to the bottom part of a gutter that is connected to a square, 50 cm long pipe by means of a wide rubber band. This square pipe leads to a 25 l container. This capacity was sufficient to minimize spillovers in the context of this study.

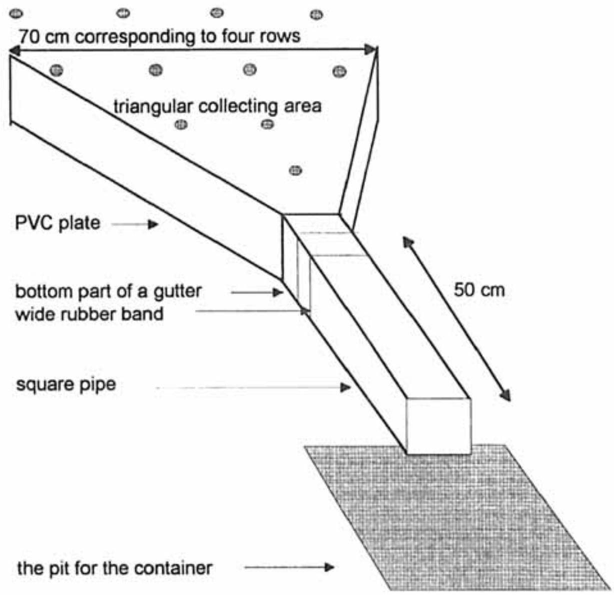

Figure 3. The device used for collecting water and sediment

The experimental design was monitored for five months, from February to June. This period had 21 wet days, three of them with a mean rainfall intensity higher than 5 mm h^{-1} (Figure 4). The amount of water collected was noted after each rainfall event. It corresponds to the runoff volume if there is no spillover. The sediment load was measured on the whole volume collected when it was lower than 250 cm^3, otherwise on aliquots of 250 cm^3 after mixing the whole volume. The containers were emptied and cleaned after each rainfall event. A runoff coefficient was estimated for each collector and each rainfall event as the ratio between the collected volume and the volume of the rainfall event corresponding to the contributive upslope area for each collector. This area is estimated as the upslope length to the collector—66, 132, 198 or 264 m—multiplied by the width of the collecting area—0·7 m—which corresponds approximately to four seed rows. This runoff contributive upslope area is correctly estimated when the rows are running directly downslope and are well defined. It is typically the case for maize fields. Here, the estimation is less precise because flow paths did not necessarily correspond exactly to the rows, especially when the relief of the rows had softened with time.

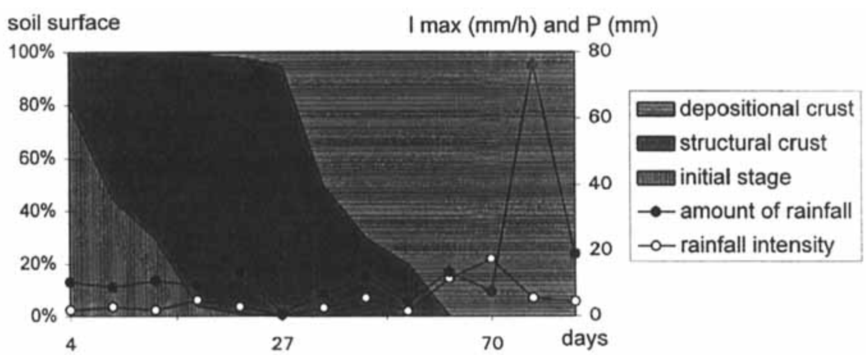

Figure 4. Amount of water by rainstorm (mm), maximum rainfall intensity (mm h^{-1}) and nature of soil surface during the study period

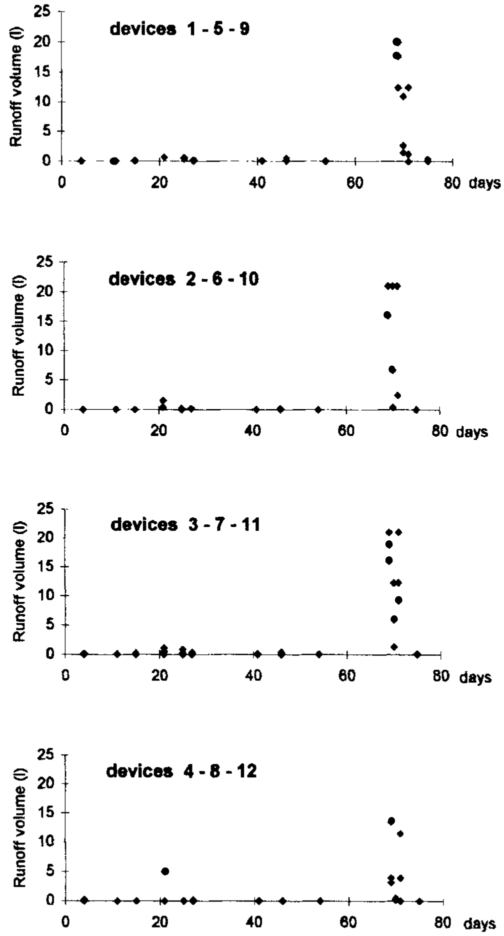

Figure 5. Runoff volume versus time and versus the position on the slope: three values for each corresponding to the three collectors located at the same position on the slope

The condition of the soil surface was described according to the classifications by Bresson and Boiffin (1990), Bresson and Valentin (1990) and Valentin and Bresson (1992) during the study period and at the four positions on the slope. Only three conditions have been distinguished: initial soil surface, structural crust and depositional crust (Figure 4). The proportions of soil surface covered by the different conditions for a given date are mean values for the whole field; no difference was observed between the different plots of the same position on the slope. A small difference was observed, though not precisely quantified, between the plots located at different positions on the slope: the soil surface crusting is slightly slower downslope than upslope, probably due to the variation of soil composition on the slope (Table I).

RESULTS

No runoff occurred as long as there was no crust at the soil surface and no heavy rain (Figure 5). A small and randomly distributed runoff was measured during April, corresponding to moderate rainfall intensity, an incomplete development of the soil surface crust and vegetation cover. Runoff was five to ten times higher in June when the rainfall intensity was high and the sealing crust was well developed, despite a continuous vegetation cover. The runoff volume depended both on the local slope steepness and the position on the slope. Runoff increased with slope length, though not proportionally: the runoff coefficient decreased

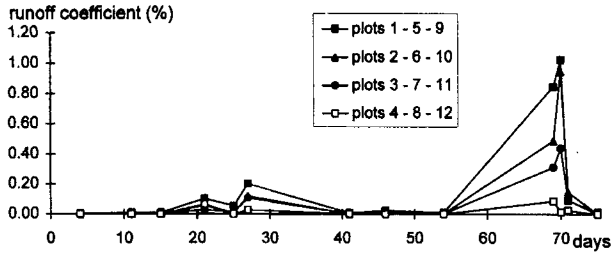

Figure 6. Runoff coefficient versus time and versus the position on the slope: mean values calculated for each set of three collectors located at the same position on the slope

with the slope length (Figure 6). It was almost halved from one position on the slope to the following. At the bottom, where the slope shape is concave, the runoff volume was small, or even nil.

The overland flow remained as a thin sheet flow on the hillslope without any location of concentrated flow according to the slope; infiltration of surface water en route downslope was important. Surface water did not flow out of the field but infiltrated in the concave downslope area. The logarithm of the mean and of the standard deviation, estimated from the measurements of the three collectors located at the same position on the slope during the whole study period, are linearly related (Figure 7): no scatter appears for the high values of runoff. This may be a particular feature of sheet flow as opposed to concentrated overland flow. It the case of sheet flow, the mean value for a given position on the slope, whatever its magnitude, is a good estimate of the overland flow. On the contrary, in the case of concentrated overland flow it would be difficult to estimate the mean value and the standard deviation by means of a regular network because of the high spatial variability during the heavier rainfall events, due to preferential surface flow pathways such as rills or gullies.

The sediment load was low and decreased during the study period (Figure 8). This decrease may be related to changes in the soil surface: first, the crusting, followed by the sealing crust, induced a decreasing erodibility of the soil surface for the range of observed overland flows: second, the vegetation cover increased, which decreased the raindrop detachment. The sediment load was higher downslope than on the hillslope at the beginning of the study period. These results must be considered with caution because of the difficulty in estimating the sediment load from samples. Lang (1992) showed that the sediment load is underestimated when it is measured on samples; this bias increases with the sediment load. This may partly explain the great scatter in the relationship between mean and variance for the sediment load measurements (Figure 9) compared to the relationship obtained for the runoff volume (Figure 7).

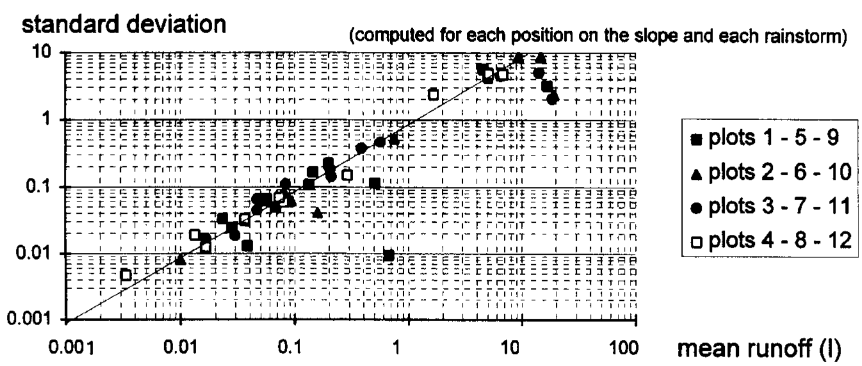

Figure 7. Standard deviation versus mean of the runoff volumes by event, for each set of three collectors located at the same position on the slope

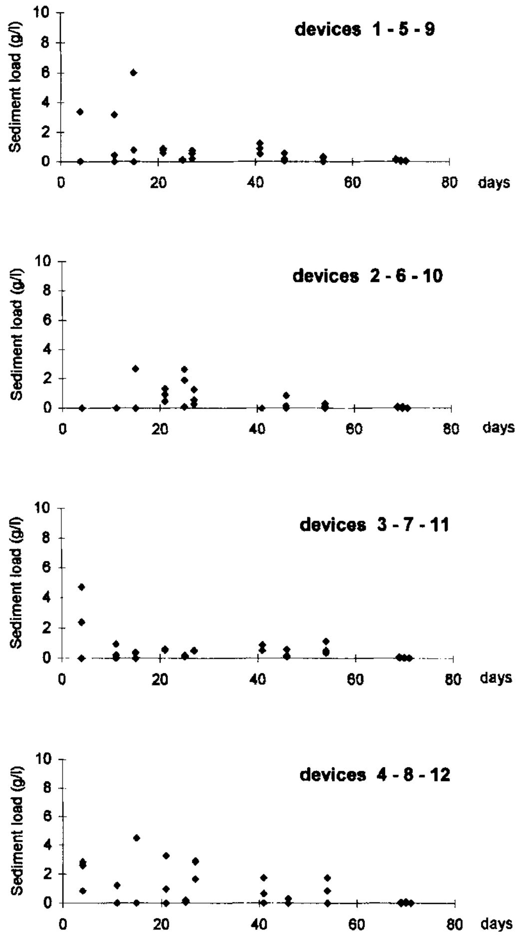

Figure 8. Sediment load versus time and versus the position on the slope: three values for each date corresponding to the three collectors located at the same position on the slope

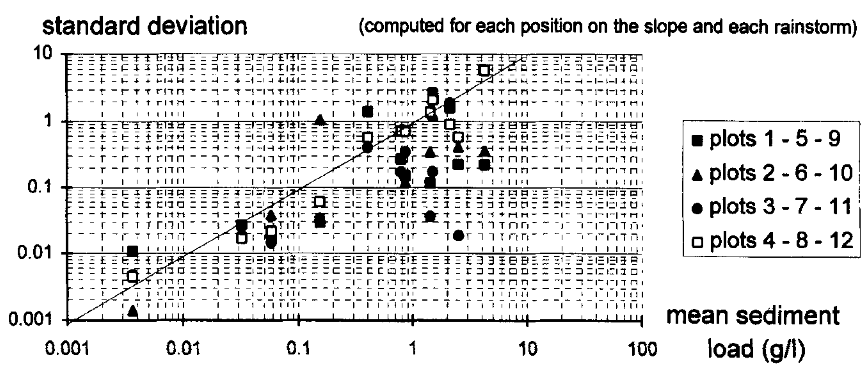

Figure 9. Standard deviation versus mean of the sediment load for the three collectors located at the same position on the slope

DISCUSSION AND CONCLUSION

The main limitation of the method used here for sheet flow measurements on hillslope is due to the unbounded upslope areas contributing to the runoff collected in the devices. The runoff coefficient is not determined accurately because these areas are not known precisely. However, in most agricultural fields the regular microrelief created by cropping, if it is parallel to the slope, allows a fairly good estimation of the contributive upslope area. The decisive advantage of the method is that it minimizes the cost and the installation time of the equipment, allowing distributed measurements through the cropping period and along the hillslope.

The results show that a noticeable redistribution of the water over the land surface occurs for each rainfall event, even though an almost nil runoff is observed at the bottom of the field. Phases of runoff generation or infiltration can be located along the slope by calculating the differences in the mean values of amount of water collected for two successive positions. For the upslope elevations, differences are always positive while they are always negative downslope: there is an upslope overland flow generation and a downslope infiltration. However, although the infiltration is mainly located in the concave part of the slope, it also occurs all along the route of water transfer.

These results demonstrate that the runoff coefficients derived from bounded plot studies are not reliable for hillslope budgets. High values obtained for plot experiments cannot be extrapolated to the hillslope scale. Conversely, nil hillslope budgets may mask an important spatial redistribution of water by sheet flow. Here, this scale effect is first related to the downslope concavity that modifies the hydraulic heads in surface and the flow velocity. Second, it may be related to slight variations of soil even spares composition (Table I) and soil crusting according to the position on the slope, which could induce variations of soil hydraulic conductivity. Third, it may be related to the spatial heterogeneity of the soil surface—cracks or biological macroporosity, depression storage, non-crusted area—which are both randomly distributed and transient as shown by the time variations of the amount of water in a given collector compared to the two others located at the same position on the slope: the longer the slope, the higher the probability for the sheet flow to meet such an area of high hydraulic conductivity.

The decrease through time of the sediment load is a function of crust and vegetation development, as often shown. Once the sealing crust is well developed and the vegetation covers soil surface, the sediment load remains low. Vegetation and sealing crust protect the soil surface from erosion processes, in this case of sheet and moderate overland flow. The values of the erosion rate are higher downslope than upslope at the beginning of the study period while the values of the runoff volume are lower downslope than upslope; this is not in agreement with Poesen's work (1992) who observed higher runoff upslope and downslope as opposed to midslope due to a slower development of the sealing crust in the steeper slopes. In only one case, the particle movement was not sufficient to form a depositional crust downslope. Further, the slight differences in texture may explain the slower development of the sealing crust downslope.

This study is the first phase of a programme on overland flow processes in cultivated areas in Brittany. It concerns only a short period of 5 months and a single field case. This will be extended to longer periods and different crops, especially maize which is likely to favour overland flow, and the winter period which induces saturation conditions. These first results showed two different risk factors for overland flow and sediment transport. The risk of overland flow and therefore of solute transfer depends strongly on the climatic conditions; the risk of sediment transport and therefore of sheet erosion depends on the nature of soil surface and the vegetation development: this relates to the short period from the crop sowing to the development of the sealing crust. For the two processes considered, the concave parts of the slope are likely to concentrate water and particles and thus associated pollutants. In this respect their environmental and hydrological role is critical. Further work is needed to study the textural, mineralogical and geochemical sorting that may coexist in time, related to the climate conditions and their consequences for the soil surface, and in space, related to the shape of the slope and the position to the stream, in order to understand the implications of water and sediment movement on pollutant transport on hillslopes.

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